Integrated Decision Support: Reducing Water Resources Vulnerability to Climate Change through Adaptive Management

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HRC

- **Integrated Decision Support Framework**
  GCM Scenarios, Downscaling, Hydrology, Water Resources

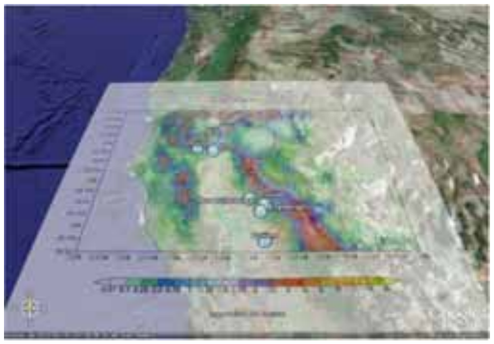
- **Climate Change Assessments for Northern California**
  Current vs. Adaptive Policies; Historical vs. Future Scenarios; Vulnerability

- **Conclusions/Further Assessments**
  Mitigation potential of adaptive, risk based management

Integrated Modeling Framework

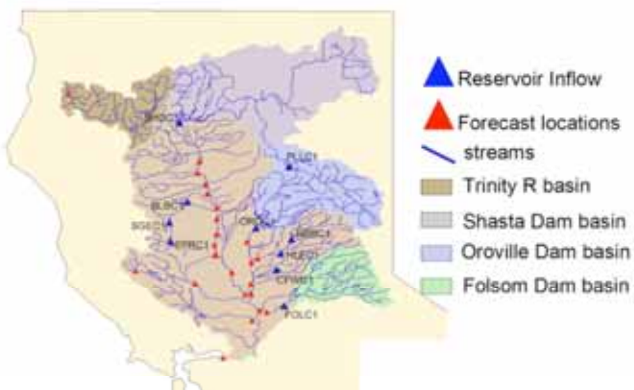
GCM Scenarios
Downscaling

Generate consistent climate forcing sequences of Rainfall and temperature.



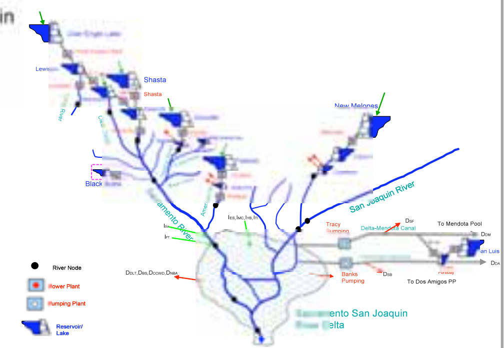
Watershed Hydrology

Simulate soil moisture, evapotranspiration, runoff, and streamflow.



River/Reservoir
Planning & Management

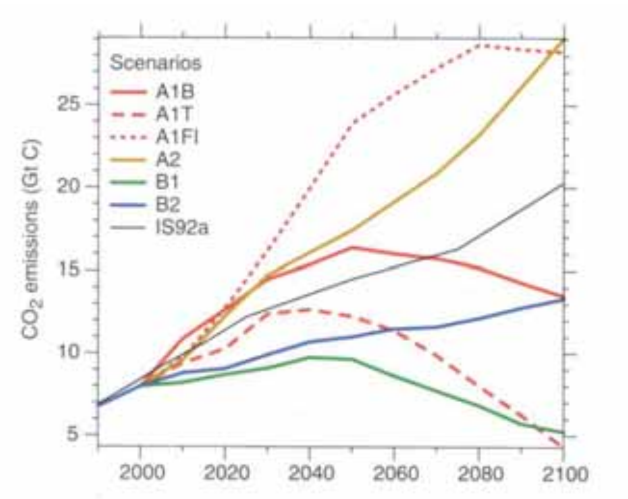
Simulate current and adaptive mgt. policies and assess impacts on water uses.

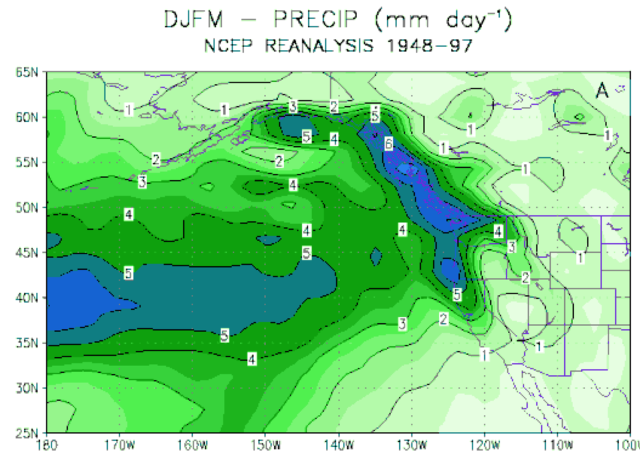


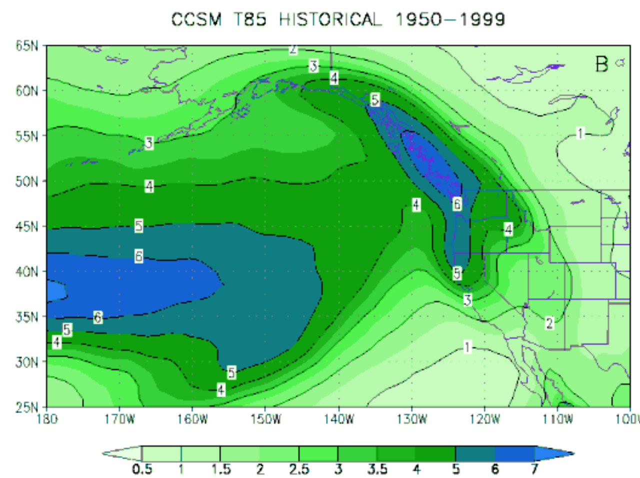
Vulnerability
Assessment
and
Mitigation Potential

Climate Scenarios

- CLIMATE MODEL: NCAR CCSM3.0 (COUPLED MODEL)
- SCENARIO: A1B MIDDLE LEVEL SCENARIO
  DECLINING EMISSIONS AFTER 2050
  MAX CO2 CONCENTRATON OF ~715 PPM AT 2100
- RESOLUTION: ~120KM HORIZONTAL RESOLUTION
  26 VERTICAL LAYERS
  6HRS TEMPORAL RESOLUTION
- VARIABLES USED: 3-D ATMOSPHERIC VARIABLES
- TWO INPUT SETS: 1970 -2019 AND 2050 - 2099







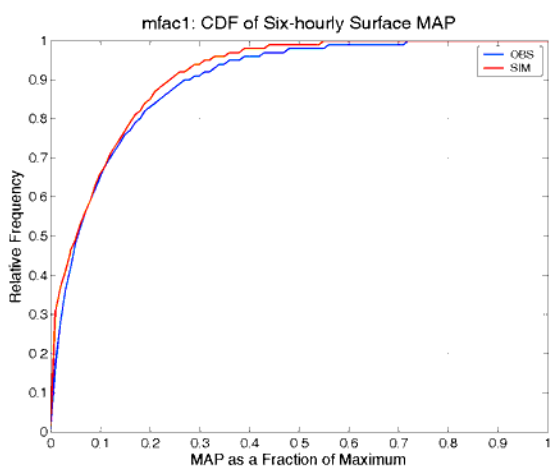
Good Large Scale Precipitation Correspondence of Historical 1950-1999 run with NCEP Reanalysis 1948-1997 for West Coast

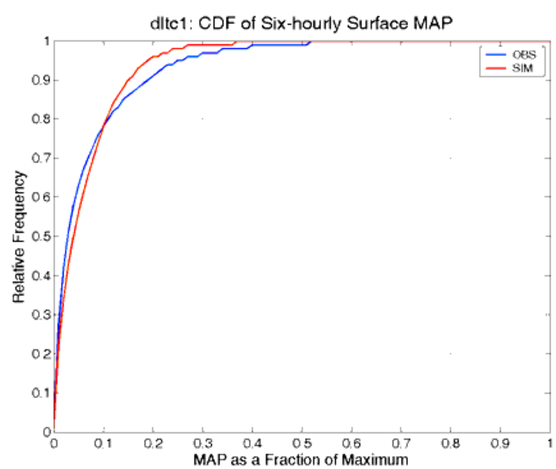
Dynamic Downscaling: Mean Areal Precipitation and Temperature

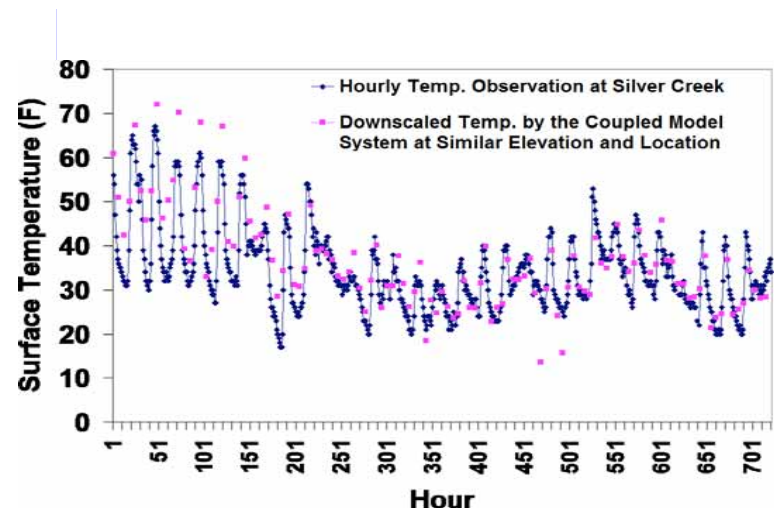
- OROGRAPHIC PRECIPITATION GRIDDED MODEL
  - WINDFLOW FROM QUASI STEADY STATE POTENTIAL THEORY FLOW
  - WATER SUBSTANCE SOURCE/ADVECTION MODEL WITH KESSLER MICROPHYSICS
  - 10X10 SQKM SPATIAL AND 6HOURLY TEMPORAL RESOLUTION

- SURFACE TEMPERATURE GRIDDED MODEL
  - INTERPOLATION/ADJUSTMENT OF CCSM3.0 LOW LEVEL TEMPERATURE OVER TERRAIN
  - SURFACE ENERGY BALANCE MODEL (OROGRAPHIC AND SNOW/SOIL MODEL COUPLING)
  - 10X10 SQKM SPATIAL AND 6HOURLY TEMPORAL RESOLUTION

- GIS-BASED SYSTEM FOR CATCHMENT DELINEATION AND PRODUCTION OF MAP AND MAT



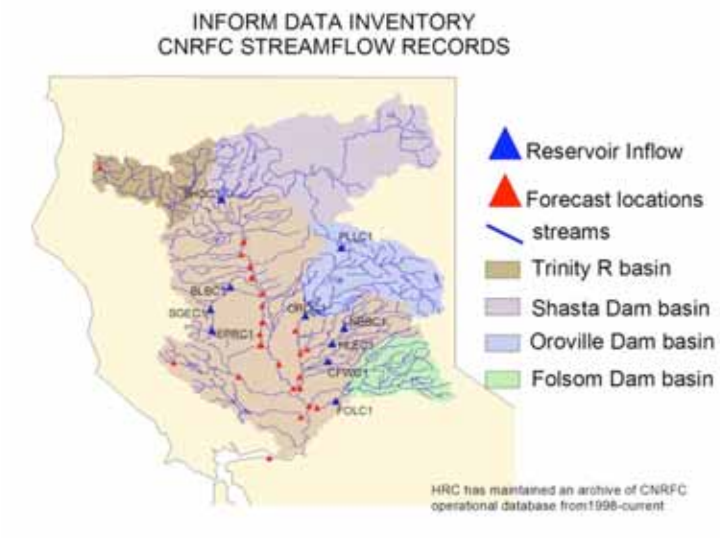




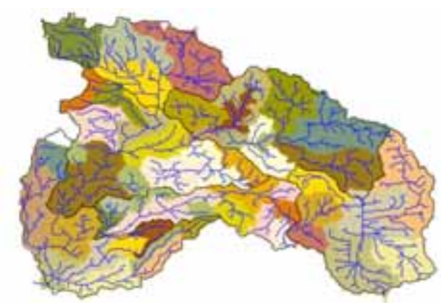
Reference: HRC-GWRI: http://www.energy.ca.gov/pier/project_reports/CEC-500-2006-109.html

Watershed Hydrology: Snow, Soil, and Channel Modeling System

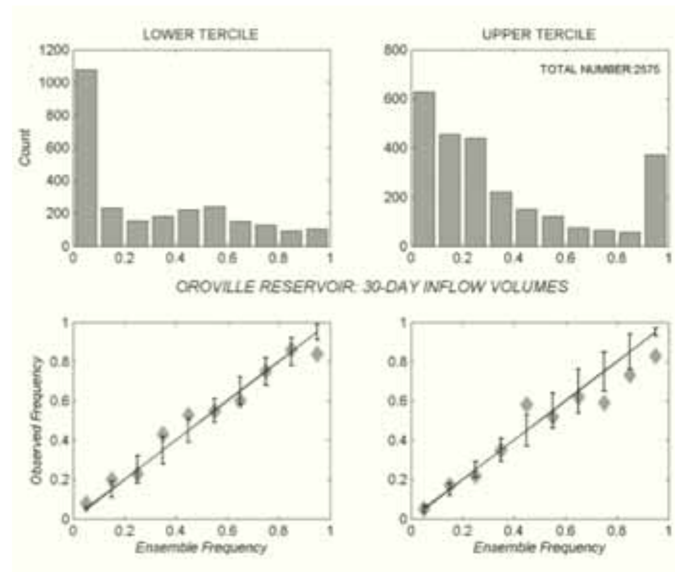
- ADAPTATION OF NWS OPERATIONAL SNOW ACCUMULATION AND ABLATION MODEL
- ADAPTATION OF NWS OPERATIONAL SOIL WATER ACCOUNTING MODEL
- KINEMATIC ROUTING THROUGH RIVER NETWORK FOR ALL BASINS



Hydrologic Model Domain



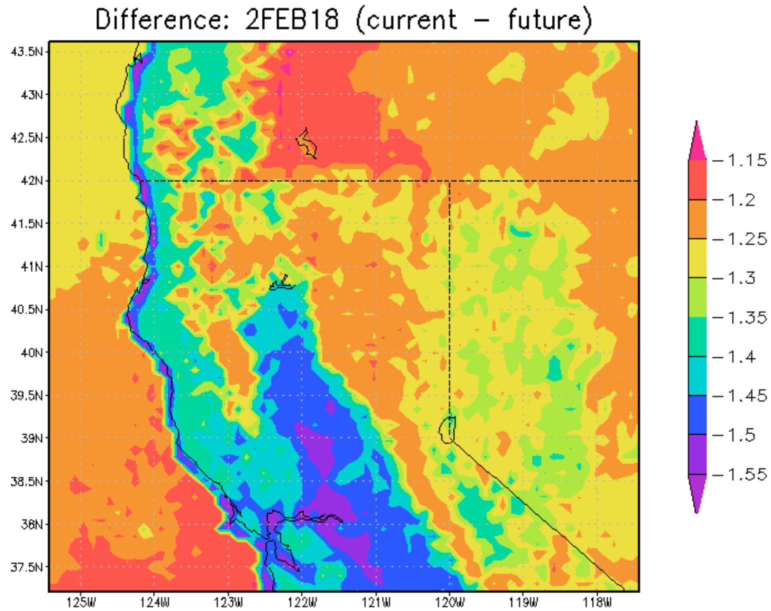
Oroville Subcatchments



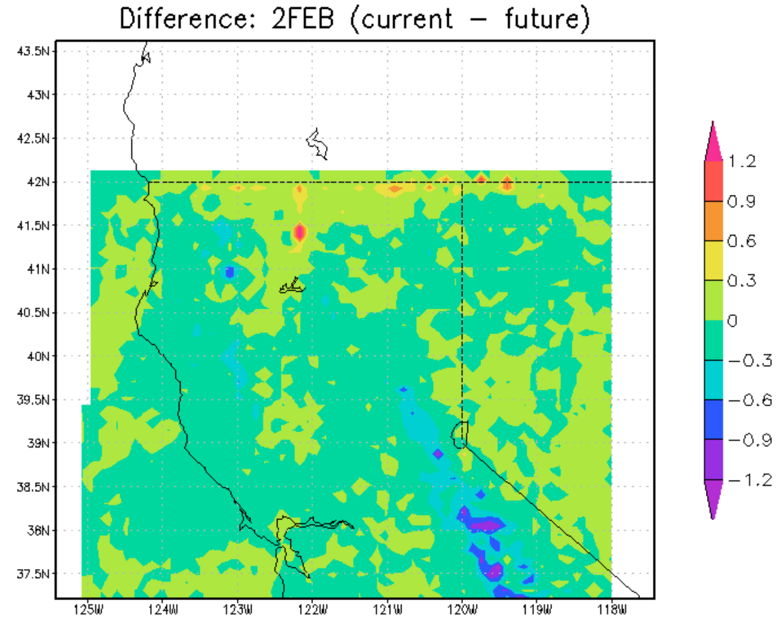
Oroville- Historical ESP Reliability Diagrams

Reference: HRC-GWRI: http://www.energy.ca.gov/pier/project_reports/CEC-500-2006-109.html

Selected Results: Temperature, Precipitation, Streamflow

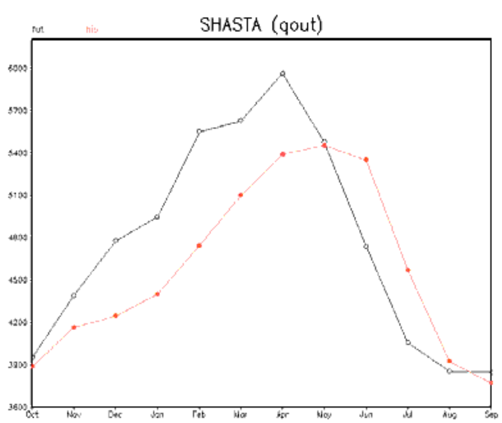


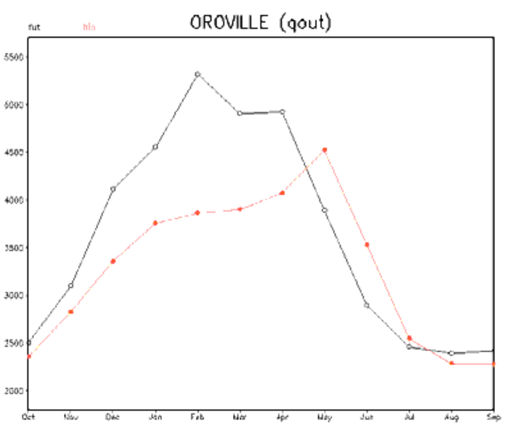
Temperature Difference (°C) – Feb 1800Z



Precipitation Difference (mm/6hrs) – Feb

- Future winters are warmer and wetter (at higher elevations) than the historical.



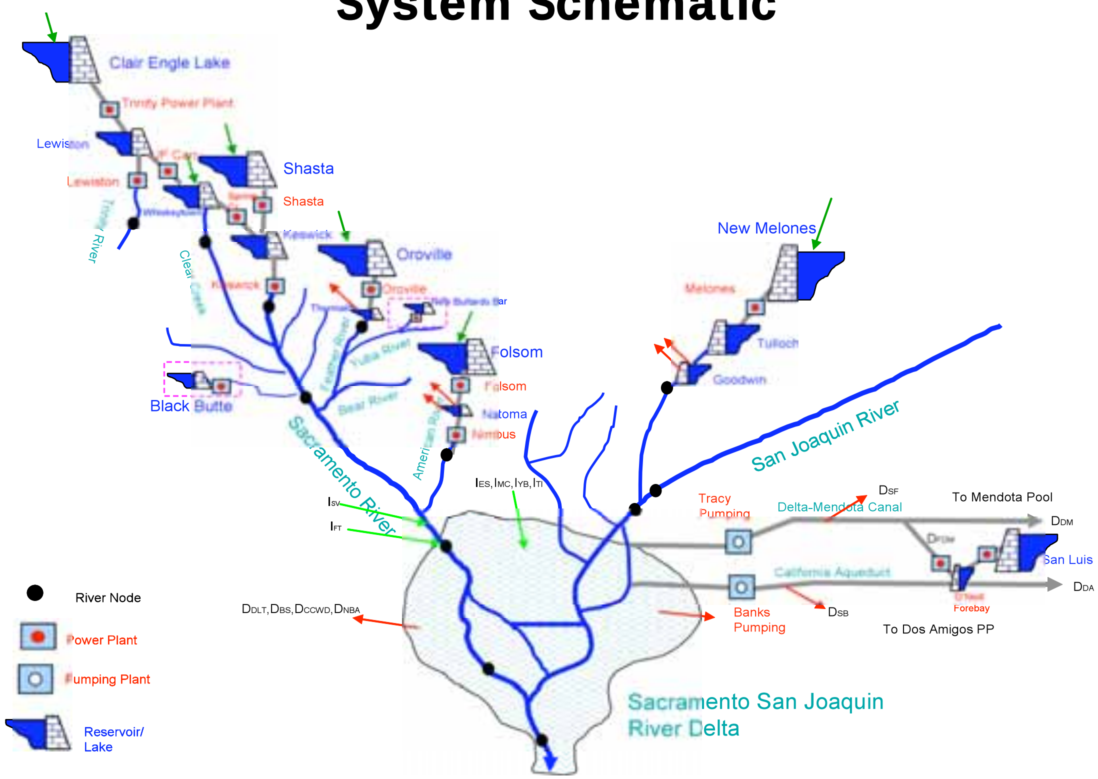


Simulated Flows:
Future
Historical

- Future flows are somewhat higher and occur earlier (Shasta/Oroville)

River and Reservoir Modeling System

Northern California River and Reservoir System Schematic



Objectives:

Water Supply
Energy Generation
Environment
Ecology
Recreation

Trinity River System (Clair Engle Lake, Trinity Power Plant, Lewiston Lake, Lewiston Plant, JF Carr Plant, Whiskeytown, Clear Creek, and Spring Creek Plant);

Shasta Lake System (Shasta Lake, Shasta Power Plant, Keswick Lake, Keswick Plant, and the river reach from Keswick to Wilkins);

Feather River System (Oroville Lake, Oroville Power Plants, Thermalito Diversion Pond, Yuba River, and Bear River);

American River System (Folsom Lake, Folsom Plant, Natoma Lake, Nimbus Plant, Natoma Plant, and Natoma Diversions);

San Joaquin River System (New Melones Lake, New Melones Power Plant, Tulloch Lake, Demands from Goodwin, and Inflows from the main San Joaquin River); and

Bay Delta (Delta Inflows, Delta Exports, Coordinated Operation Agreement--COA, and Delta Environmental Requirements).

River and Reservoir Modeling System (2)

Reservoir ID	Reservoir Name	H^{min}	H^{max}	S^{min}	S^{max}
10	Clair Engle Lake	2145	2380	313	2617
20	Whiskeytown	1000	1223	0.23	284
30	Shasta	900	1068	1167	4347
40	Oroville	640	900	852.2	3537.8
50	Folsom	327	470	83	1022
60	New Melones	800	1100	273	2571
70	Tulloch	57	67	10	20
80	San Luis	300	546	15.5	2026

Power Plant	Units	Capacity (MW)
Trinity	2	140
Lewiston	1	0.35
JF Carr	2	141.4
Spring Creek	2	150
Shasta	5	659
Keswick	3	75
Oroville	6	600
Folsom	3	210
Nimbus	2	13.5
New Melones	2	150

River Nodes
Lewiston
JF Carr
Clear Creek
Spring Creek
Keswick
Wilkins
Feather
American River
Freeport
Goodwin
SJR above Stanislaus
SJR at Vernalis
Antioch
Delta Exit

Tributary Inflows
Trinity
Whiskeytown
Shasta
Keswick-Wilkins
Oroville
Yuba River
Bear River
Folsom
Sacramento Miscellaneous
Eastside streams
Delta Miscellaneous streams
New Melones
San Joaquin River

Water Supply
Thermalito
Folsom Pumping
Folsom South Canal
OID/SSJID
CVP Contractors
CCWD
Barker Slough
Federal Tracy PP
Federal Banks On-Peak
Federal Banks Off-Peak
Federal Banks PP – Total
Federal Banks PP – CVC
Federal Banks PP - Joint Point
Federal Banks PP – Transfers
North Bay Aqueduct
State Banks PP
State Tracy PP
Delta Mendota Canal
Federal Dos Amigos
Federal O'Neil to Dos Amigos
San Felipe
Cross Valley Canal
Federal Exchange O'Neil
Federal Exchange San Luis
South Bay/San Jose
State Dos Amigos
Delta Consumptive Use
Freeport Treatment Plant
Yolo Bypass
Transfer Inflow

AFRP (Anadromous Fish Restoration Plan)
Clear Creek Below Whiskeytown Lake (Trinity)
Below Keswick Dam (Sacramento)
Below Nimbus Dam (American)

River and Reservoir Modeling System (3)

Base Demand Locations and Amounts (WS Deliveries)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Thermolito	35	0	11	67	189	178	200	178	78	95	104	71
Folsom Pumping	4	4	4	7	8	12	13	12	10	7	5	4
Folsom South Canal	1	1	1	1	2	3	4	4	3	2	1	1
OID/SSJID	0	0	14	60	90	90	95	95	74	14	0	0
CVP Contractors	0	0	0	0	0	0	0	0	0	0	0	0
CCWD	14	17	18	18	14	14	13	13	13	10	11	13
Barker Slough	2	2	1	2	4	5	7	7	6	5	3	3
Federal Tracy PP	258	233	258	250	135	169	270	268	260	258	250	258
Federal Banks On-Peak	0	0	0	0	0	0	28	28	28	0	0	0
State Banks PP	390	355	241	68	108	125	271	278	238	175	193	390
State Tracy PP	0	0	0	0	0	0	0	0	0	0	0	
Delta Mendota Canal	30	60	100	120	190	220	270	240	180	110	40	30
Federal Dos Amigos	40	50	60	70	110	180	238	178	68	30	30	30
Federal O'Neil to Dos Amigos	0	1	1	1	1	2	2	1	0	0	0	0
San Felipe	6	6	10	15	19	20	21	20	13	11	8	8
South Bay/San Jose	2	2	2	5	5	7	7	8	7	12	8	6
State Dos Amigos	105	127	158	105	348	348	423	388	269	229	196	61
Delta Consumptive Use	-56	-37	-10	63	121	191	268	252	174	118	55	2

Delta-related Model Variables (68)

GroupID	SeqID	SeqName
Delta Inflows	1	Sac Valley Acc/depl
Delta Inflows	2	Freeport Treatment Plant
Delta Inflows	3	Freeport Flow
Delta Inflows	4	SJR at Vernalis
Delta Inflows	5	Eastside Streams
Delta Inflows	6	Misc Creeks Inflow
Delta Inflows	7	Yolo Bypass
Delta Inflows	8	Transfer Inflow
Delta Inflows	9	Total Delta Inflow
Delta Exports	10	CCWD Diversion
Delta Exports	11	Barker Slough
Delta Exports	12	Federal Tracy PP
Delta Exports	13	F. Banks On-Peak FBON
Delta Exports	14	F. Banks Off-Peak FBOFF
Delta Exports	15	Federal Banks PP - Total
Delta Exports	16	Federal Banks PP - CVC
Delta Exports	17	Federal Banks PP - Joint Point
Delta Exports	18	Federal Banks PP - Transfers
Delta Exports	19	Total Fed Pumped Planned
Delta Exports	20	Total Fed Pumped Computed
Delta Exports	21	Total Federal Export Planned
Delta Exports	22	Total Federal Export Computed
Delta Exports	23	NBA Diversion
Delta Exports	24	State Banks PP
Delta Exports	25	State Tracy PP
Delta Exports	26	Total State Export Planned
Delta Exports	27	Total State Export Computed
Delta Exports	28	Total Exports Planned
Delta Exports	29	Total Exports Computed
Delta COA	30	Required Delta Outflow
Delta COA	31	Delta Consumptive Use
Delta COA	32	Req. Combined Res. Release
Delta COA	33	Computed Delta Outflow
Delta COA	34	Excess Outflow
Delta COA	35	Total Federal Storage Withdrawal
Delta COA	36	State Storage Withdrawal
Delta COA	37	Unstored Flow for Export
Delta COA	38	Est. In-Basin Use of Stor. With.
Delta COA	39	USBR Allowable Export
Delta COA	40	USBR Monthly COA Account
Delta COA	41	Accumulated COA
Delta COA	42	Rio Vista Flow
Delta Environment	43	X-channel Gates
Delta Environment	44	Cross Delta Flow
Delta Environment	45	Antioch Flow
Delta Environment	46	QWEST Calculated
Delta Environment	47	Inflow Diverted Std%
Delta Environment	48	Inflow Diverted % Computed
Delta Environment	49	X2 Location (km from GG)
Delta Environment	50	Supplemental Project Water (Term 91)
Delta South	51	Delta Mendota Canal
Delta South	52	Federal Dos Amigos
Delta South	53	F.D. . ON to DA
Delta South	54	S. Felipe Demands
Delta South	55	Cross Valley Demand
Delta South	56	Fed to S Ex. in ON
Delta South	57	Fed to S Ex. in SL
Delta South	58	Fed SL P/G.
Delta South	59	Federal Storage
Delta South	60	S. Bay/ N S.J.
Delta South	61	State Dos Amigos
Delta South	62	State SL P/G.
Delta South	63	State Storage
Delta South	64	Total SL Storage
Delta South	65	SL Area
Delta South	66	SL Elevation
Delta South	67	SL Est. Evap.
Delta South	68	SL Evap Coefficients

Delta Inflows

Delta Exports

Delta COA

Delta Environment

Delta South

River and Reservoir Modeling System (4)
Current and Adaptive Management Policies

Current Policy

- Generate inflow forecasts—median trace (HA).
- Determine water year type (DWR: C/D/N/AN/W).
- Adjust base demands based on year type.
- Determine next month reservoir releases to
  - meet water delivery targets and minimum required flows at various river nodes,

  assuming no extra releases are required to meet Delta demands (X2) and pumping to South CA.
- If X2 requirements and south CA delivery targets are not met, increase releases according to COA (roughly 25/75 rule).
- If deficits persist, allocate water to meet X2 first, then south CA water deliveries.
- Repeat at the next month.

Adaptive, Risk-based Policy

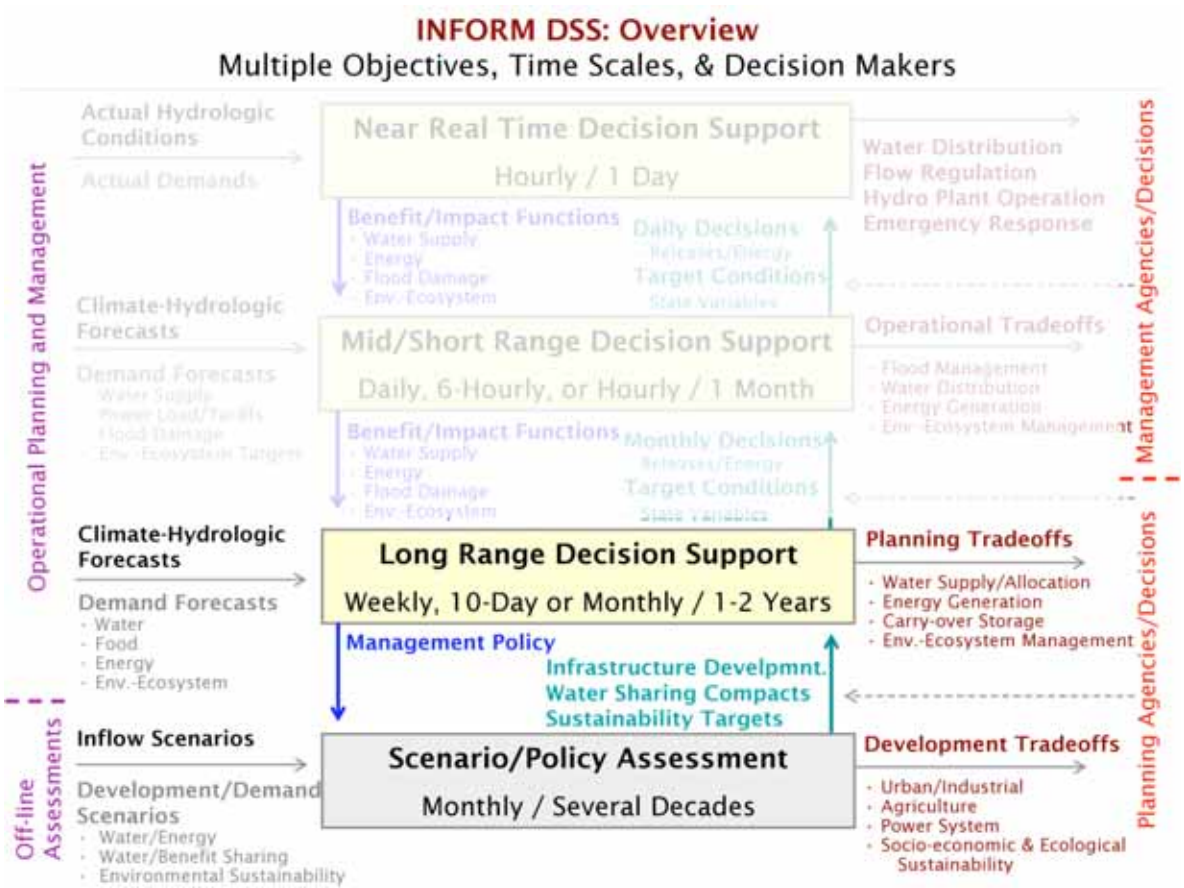
- Generate inflow forecasts—full ensemble (HA).
- Determine reservoir releases for the next 9 months to
  - meet water delivery targets and minimum required flows at various river nodes,
  - meet environmental and ecological Delta requirements associated with the X2, location and Delta outflow,
  - generate as much energy as possible, and
  - maintain high reservoir levels and sufficient carry-over storage.

  (*System-wide, stochastic optimization; Not according to the COA.*)
- Apply first month release and repeat.

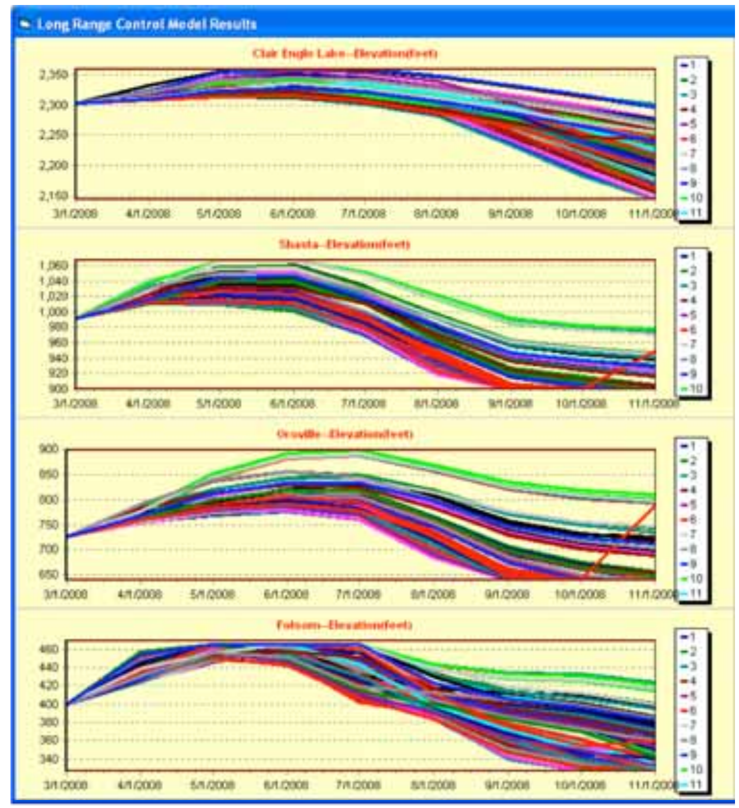
Main Policy Differences

Current Policy	Adaptive Policy
Focuses on current month.	Optimizes over the next 9 months.
Deterministic.	Risk based.
Adjusts demand targets twice a year.	Re-optimizes every month.
Follows COA in extra water allocation.	Finds optimal allocation strategy each time.

Adaptive Management System (INFORM DSS)

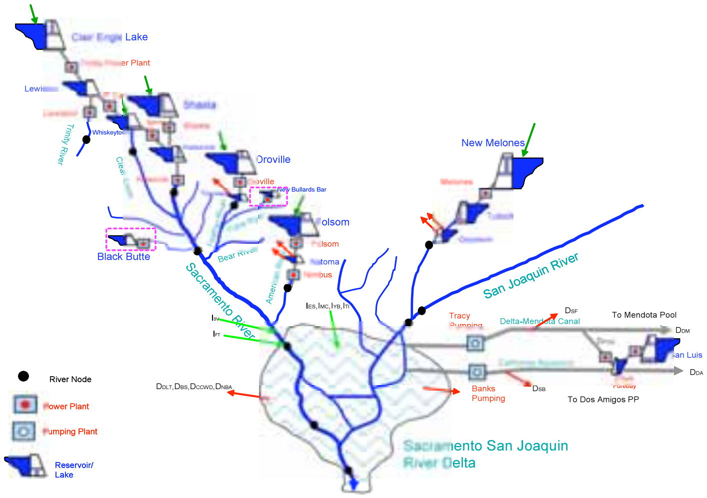


System-wide, stochastic optimization



Reference: HRC-GWRI: http://www.energy.ca.gov/pier/project_reports/CEC-500-2006-109.html

Assessment Process



9-month Forecast-Decision Horizon

Inflow Forecasting

River/Reservoir Simulation

Reservoir Mgt. Basin wide

Management Policy

Assessment Criteria

Lake Levels, Spillage

Water Supply Reliability

Energy Generation

Bay Environment (X2)

others.

Inflow Scenario

Demand Scenario

Regulation Policy

(Monthly time steps)

One Step System Simulation

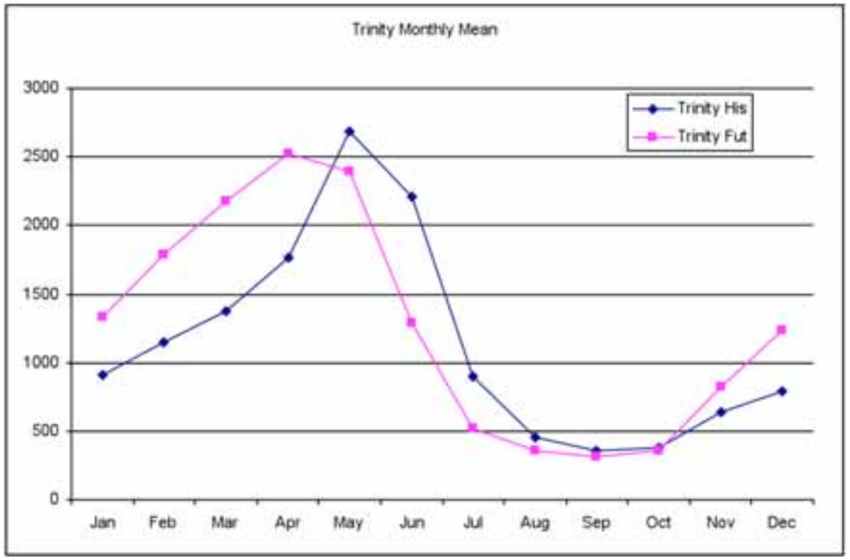
Simulation Horizon

1970 to 2019 (Historical)

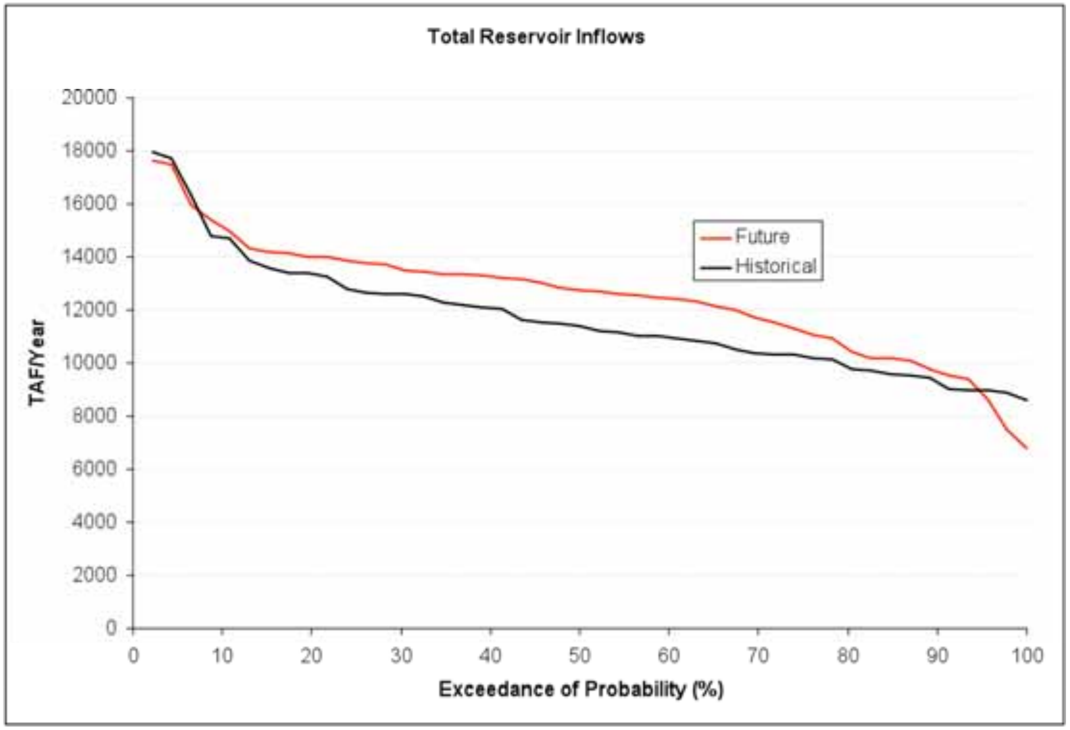
2050 to 2099 (Future)

Inflow Comparison (Historical vs. Future Scenario)

Trinity Historical vs. Future Inflows



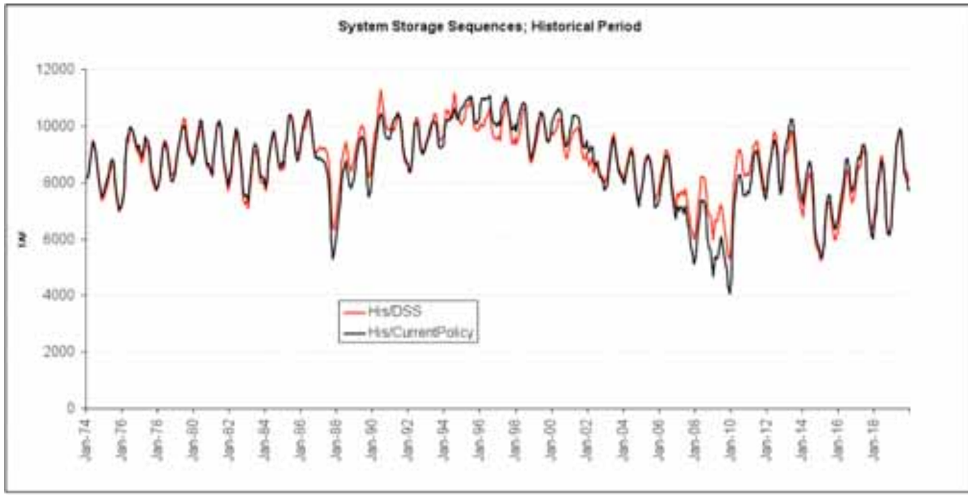
System Historical vs. Future Inflows



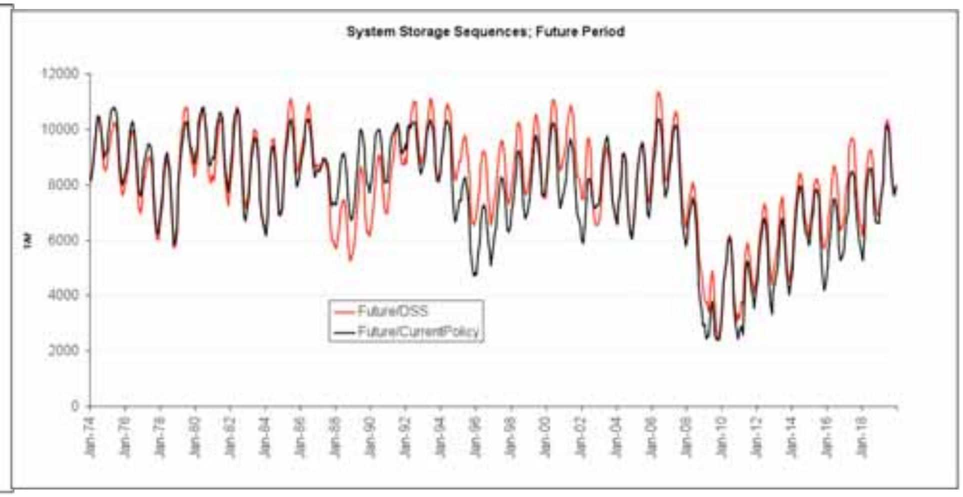
- **Average future inflows are somewhat higher**.
  (Trinity **6.3%**; Oroville **10%**; Shasta **4.3%**; Folsom **5.6%**.)
- Minimum future inflows are considerably lower indicating **more severe droughts** (**27%** reduction).
- Future inflows are more variable.
- **Wet season shifts earlier**.

Lake Levels: Current vs. Adaptive Policies for Historical and Future Scenarios

Historical



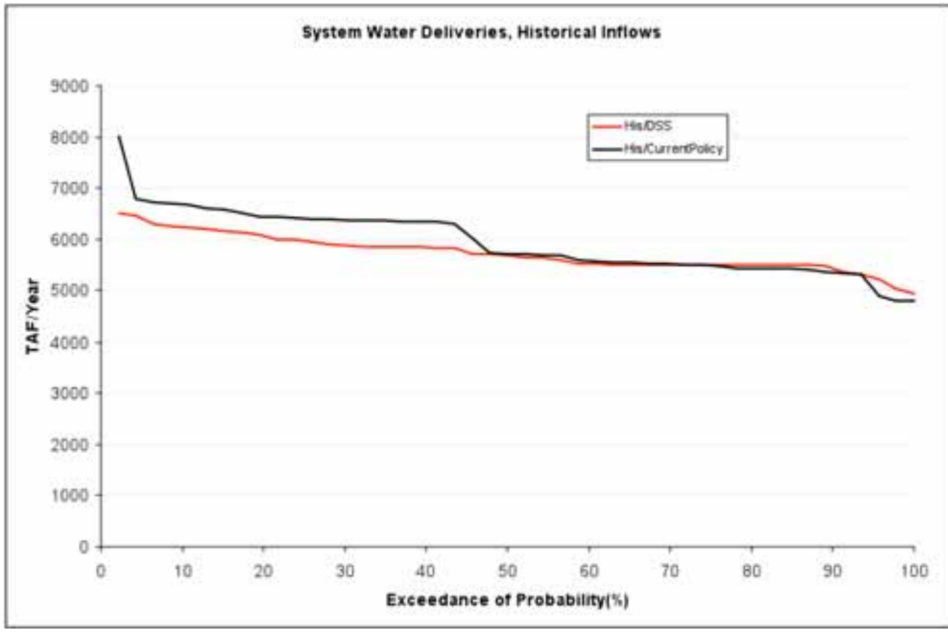
Future



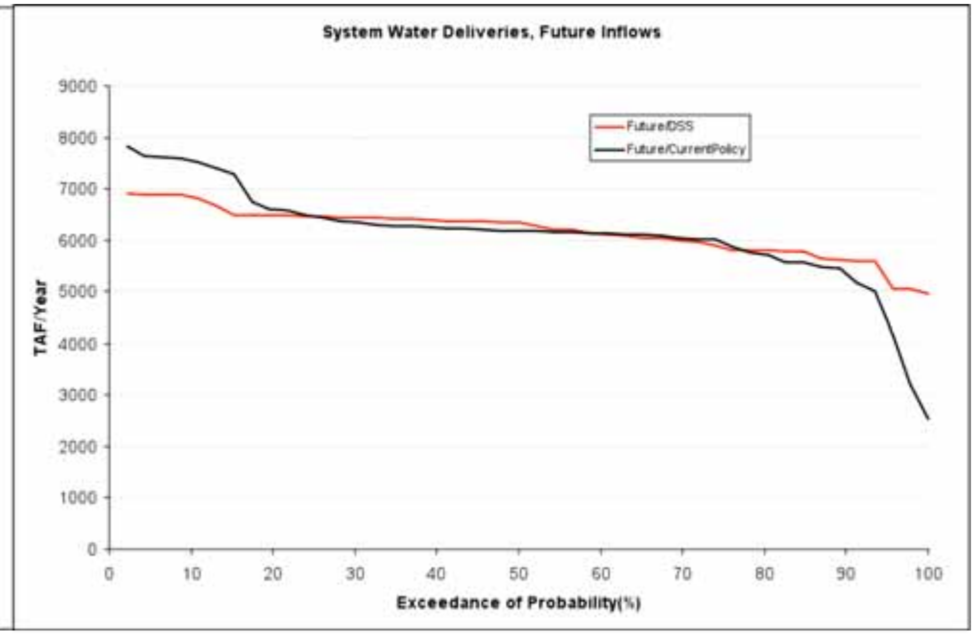
- Lake levels exhibit considerably **greater seasonal and annual variability** in the future scenario.
- System conservation storage is used up in the future scenario. **Drought vulnerability increases**.
- Adaptive DSS policy exhibits **higher lake levels and less spillage** than current policy.

Water Deliveries: Current vs. Adaptive Policies for Historical and Future Scenarios

Historical



Future

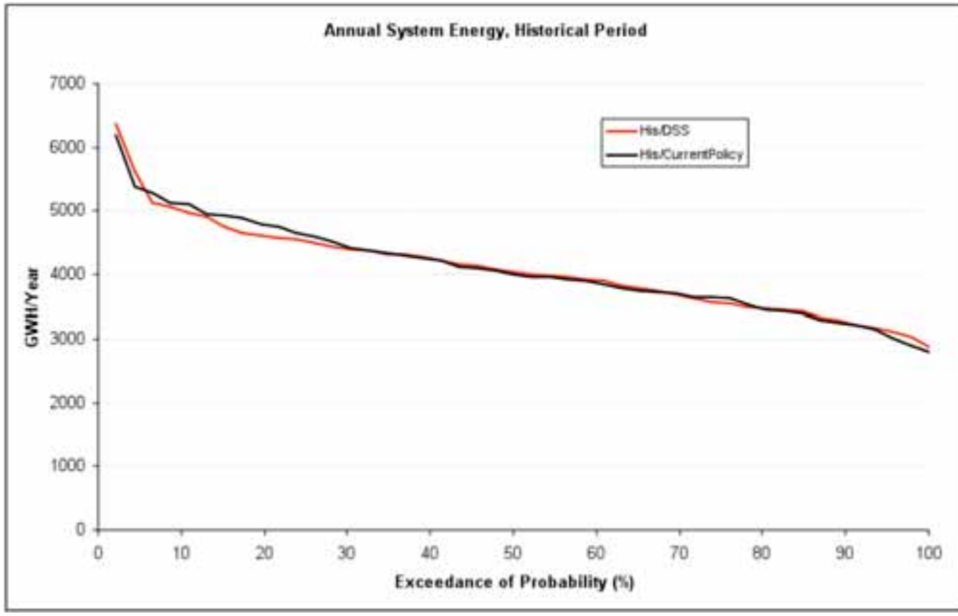


- Current policy provides higher amounts during wet years and lower during dry years. **Adaptive DSS policy is more balanced and reliable—reduces vulnerability**.

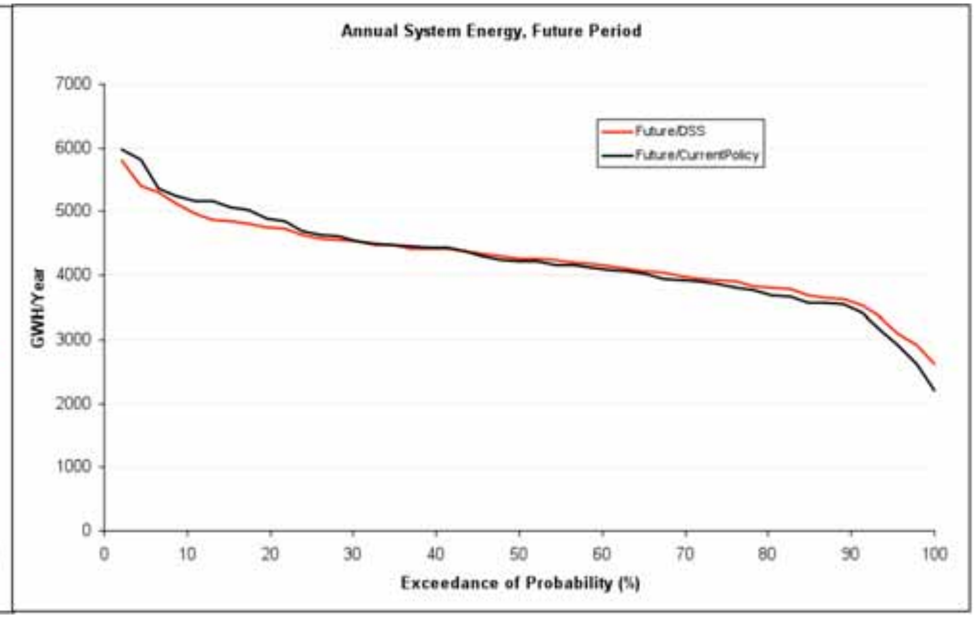
- Current policy WS during most severe drought (TAF): 4,798 (Historical); **2,545** (Future)
  Adaptive DSS WS during most severe drought (TAF): 4,923 (Historical); **4,949** (Future)

Energy Generation: Current vs. Adaptive Policies for Historical and Future Scenarios

Historical



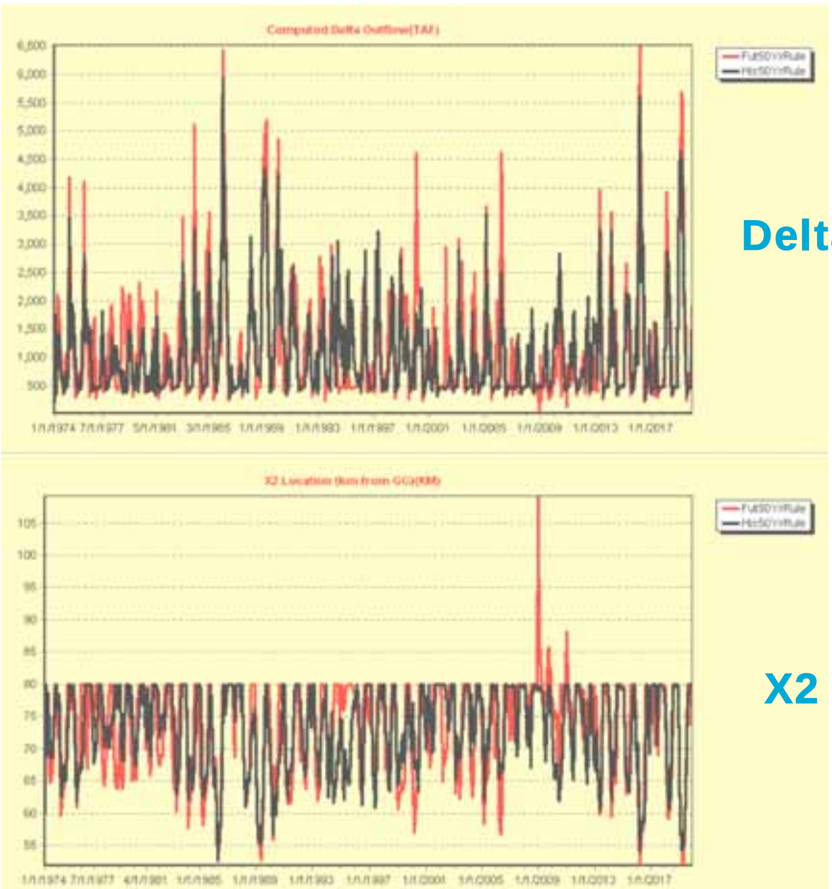
Future



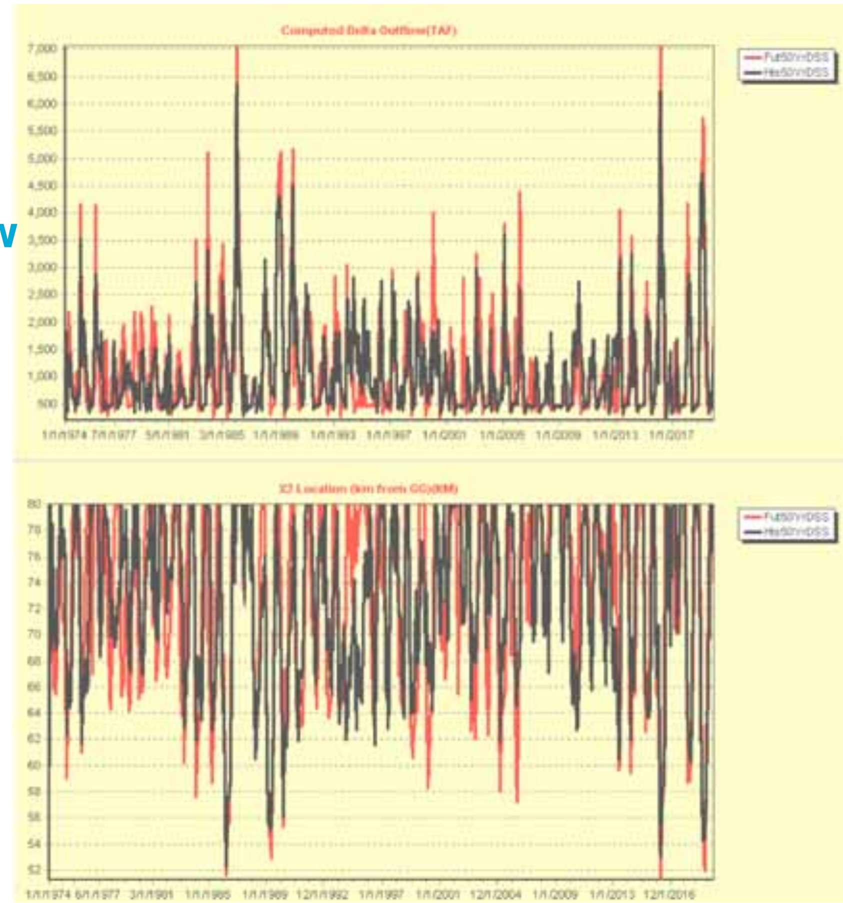
- **Average** energy generation **increases by 5%** in the future scenario under both policies.
- **Firm** energy generation **decreases by 10% under the Adaptive Policy and 29% under the Current Policy**.

Delta Outflow and X2 Location: Current vs. Adaptive Policies for Historical and Future Scenarios

Current Policy



Adaptive DSS Policy

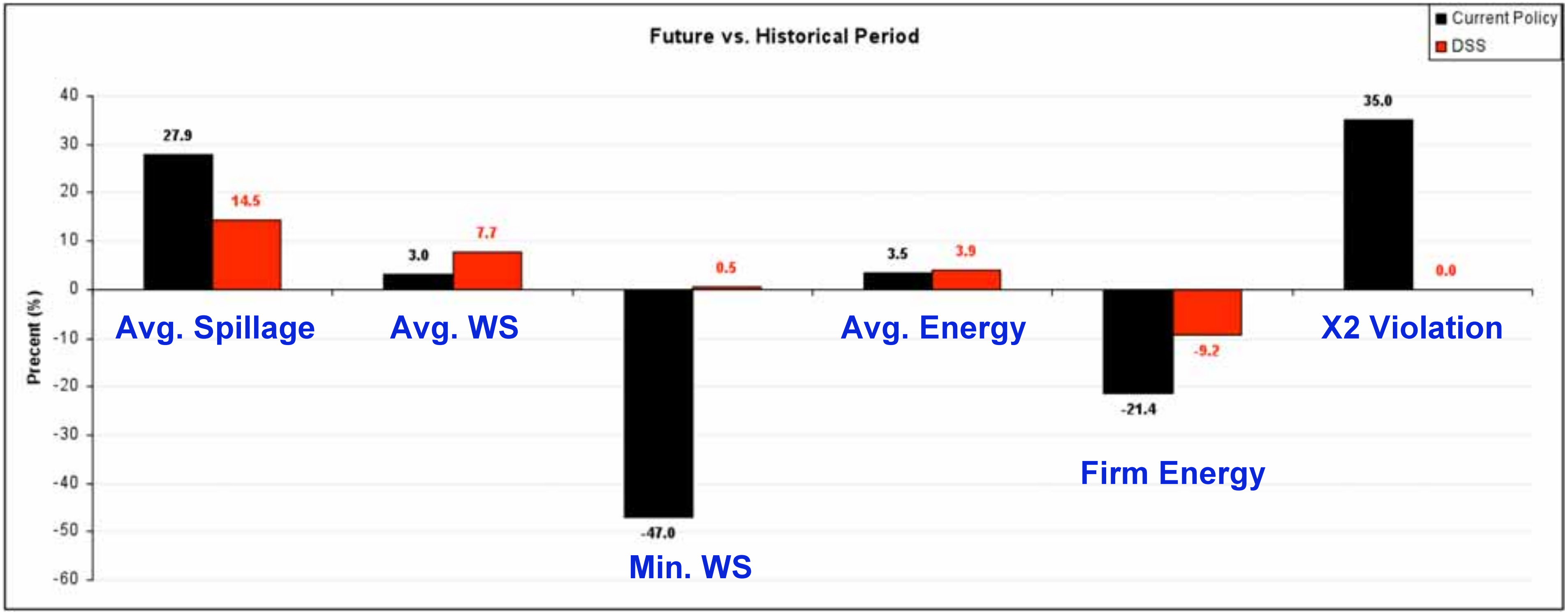


Delta Outflow

X2 Location

- Adaptive DSS policy **meets** **Delta outflow and X2 requirement** in both scenarios. Current Policy **violates** **Delta outflow and X2 requirement** (by 28 kilometers) in future droughts.

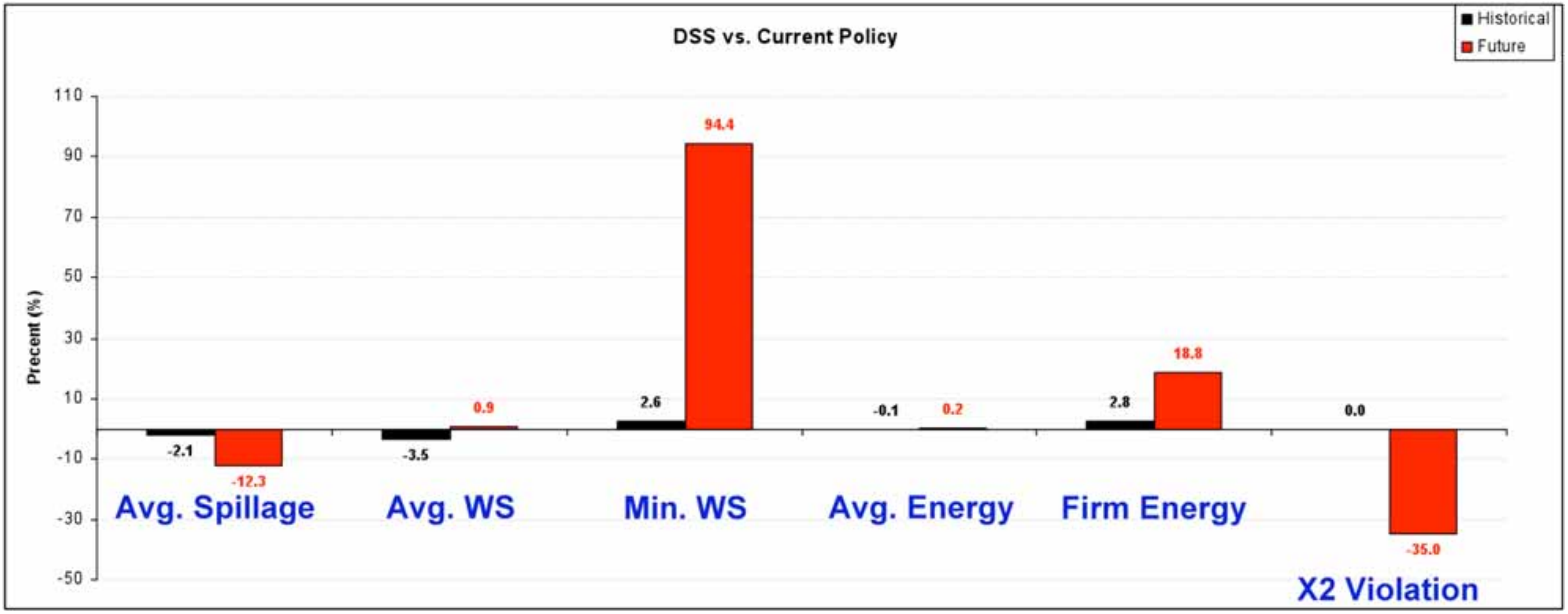
Performance Differences (%) of Future relative to Historical Scenario



- **Current policy worsens in the future scenario**:
  - − More spillage (27.9%), less minimum water deliveries (47%), less firm energy (21.4%), and significant X2 and delta outflow violations (35%).
  - \+ Increased average water deliveries (3%) and energy generation (3.5%).

- **Adaptive DSS policy more robust** between historical and future scenarios:
  - \+ Increased average water deliveries (7.7%), increased minimum water deliveries (0.5%), increased average energy (3.9%), and no X2 and delta outflow violations.
  - − Increased spillage (14.5%), less firm energy (9.2%).

Performance Differences (%) of DSS relative to Current Policy



- **Adaptive DSS vs. Current Policy differences are minor in the historical scenario.**

- **Adaptive DSS policy is notably more robust in the future scenario with respect to all criteria,** especially minimum water supply, firm energy, Delta requirements, and spillage.

- There are **nonlinear interactions and tradeoffs underlying system response and performance against the different criteria**. Such assessments serve to quantify and communicate these interdependencies.

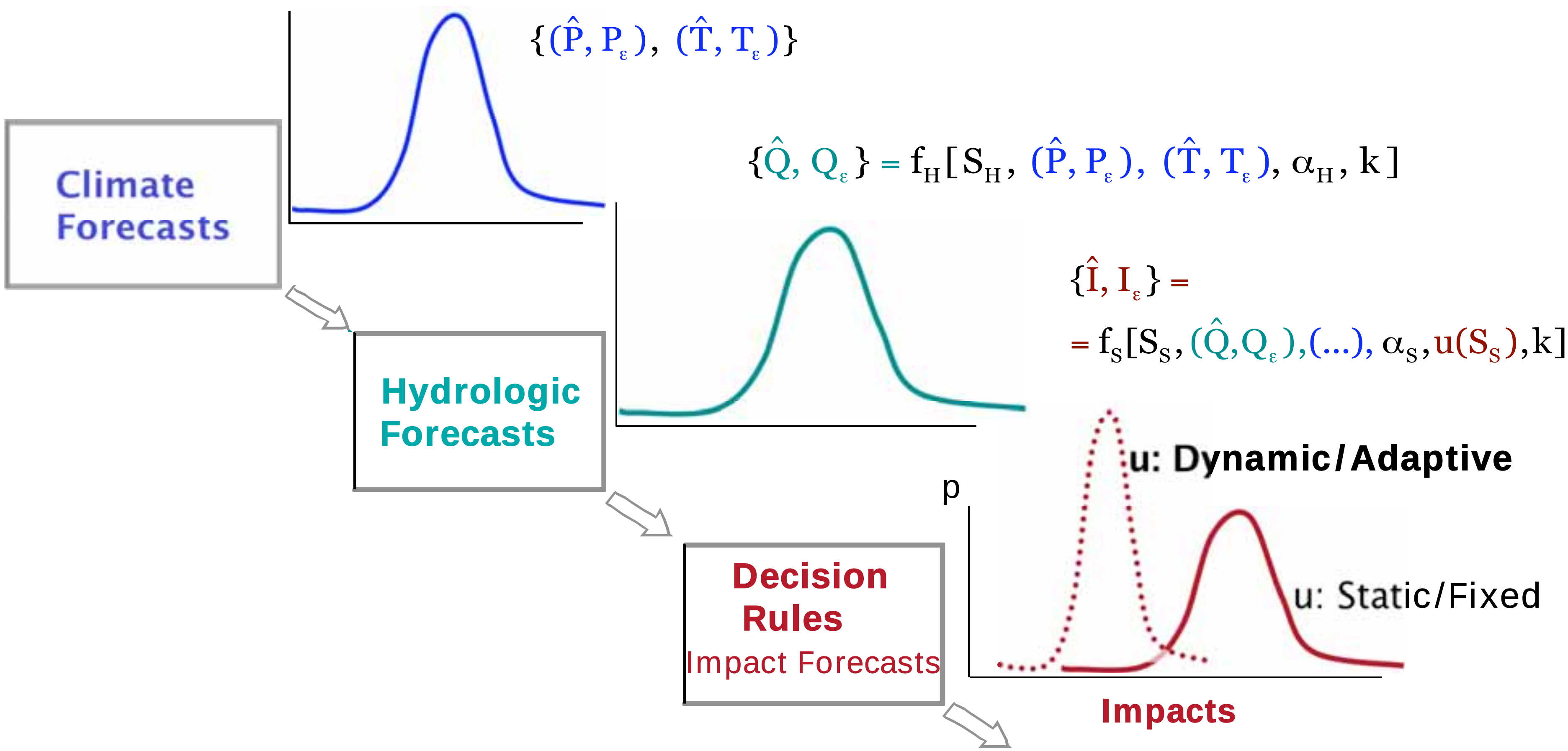
Conclusions

- Future A1B scenario portents **intensifying water stresses** (due to seasonal inflow shifts and higher inflow variability) and **higher vulnerability to extreme droughts**.

- Adaptive, risk based, reservoir regulation strategies are **self tuning to the changing climate**, deliver **more robust performance than current management practices**, and can considerably **mitigate the negative impacts of increased water stresses**.

- Effective implementation of adaptive, risk based, reservoir regulation strategies require
    - **more flexible laws and policy statutes** (COA, heuristic rules, etc.),
    - a **new level of institutional cooperation** for water resources management, and
    - **capacity building** of agency personnel in modern decision support methods.

Uncertainty Management: Climate → Hydrology → Management



Impacts

Flood Damage, Water Supply,
Energy Generation, Agriculture
Public Health, etc.

Adaptive decision rules can **manage** forecast uncertainty.

Heuristic regulation rules cannot.

Further Work

- Bracket **cloud influence** in climate downscaling component.
- Incorporate impacts of **sea-level rise**.
- Assessments of **other GCM scenarios** (A2, B1, etc.) to investigate the sensitivity of the findings presented herein.
- Assessments with **daily and sub-daily temporal resolution** to quantify climate change impacts on other system functions and outputs (flooding, energy generation markets, ecosystem response, etc.).
- Multi-stressor assessments including **demand and land use change**.
- Conjunctive, statewide **surface water – groundwater** assessments.

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